Constraining the Early Universe with Gravitational Waves

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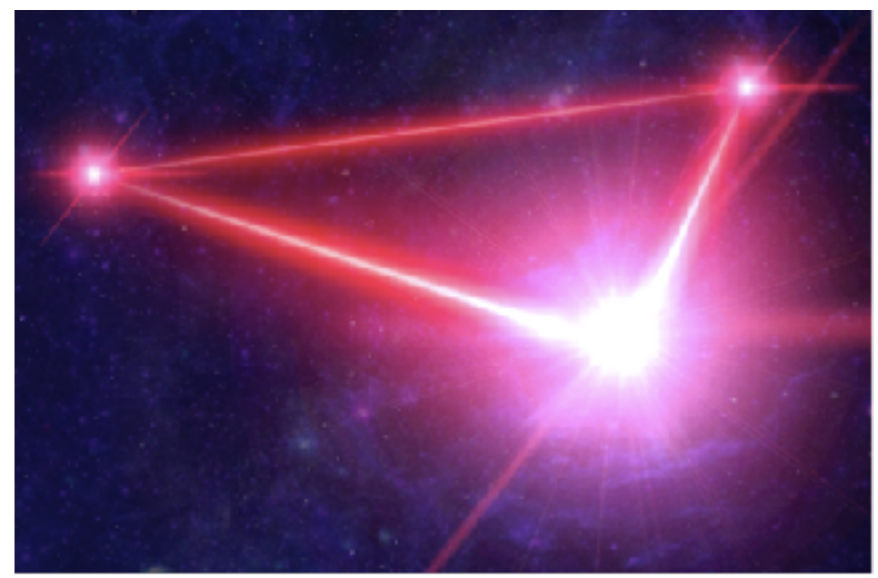
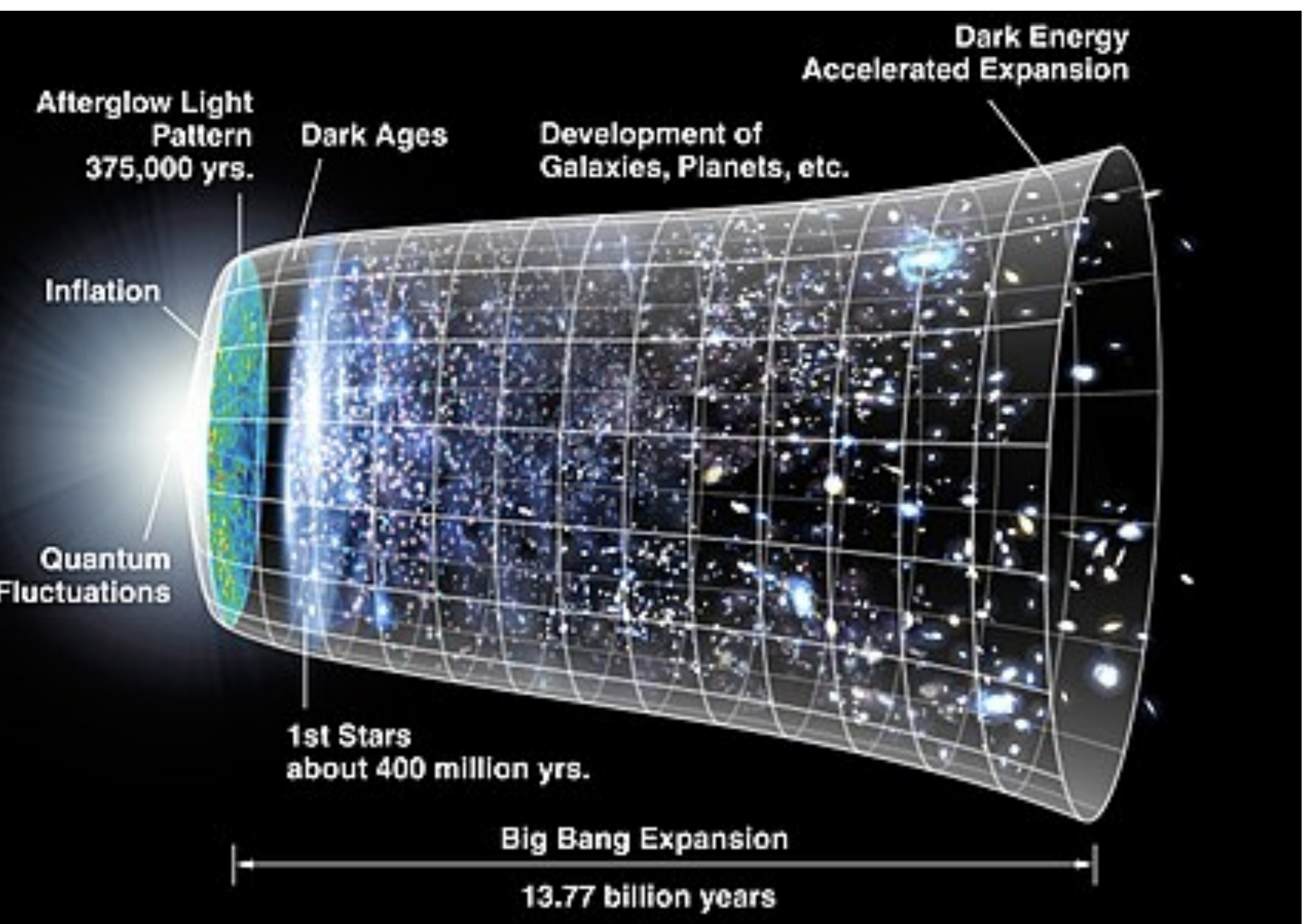
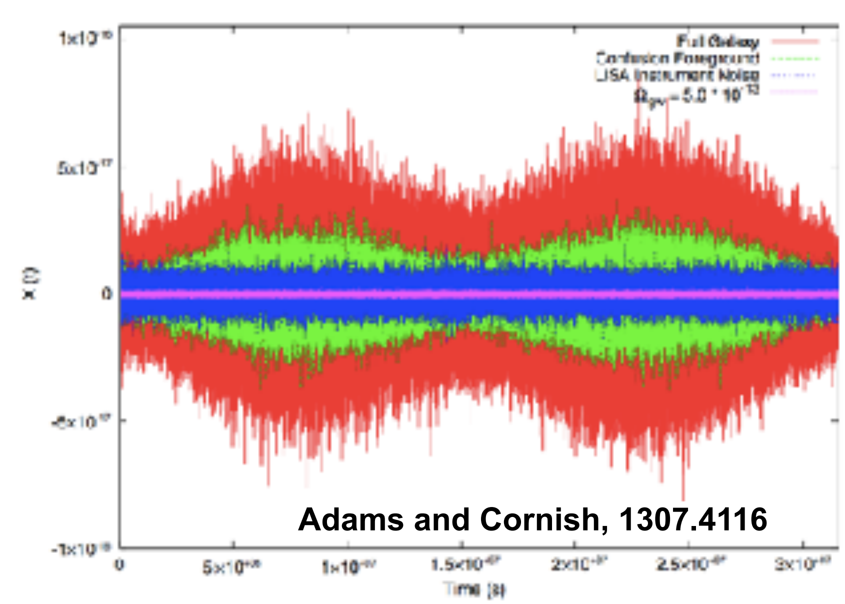






GW and cosmology: observational scientific context

- Several direct GW detections by the Earth-based interferometer network LIGO/Virgo since 2015
  we have a new observable to probe the universe

- GW170817 NS binary merger: first coincident detection of GW and EM signals, measure of Hubble factor
  GW have the potential to constrain cosmology

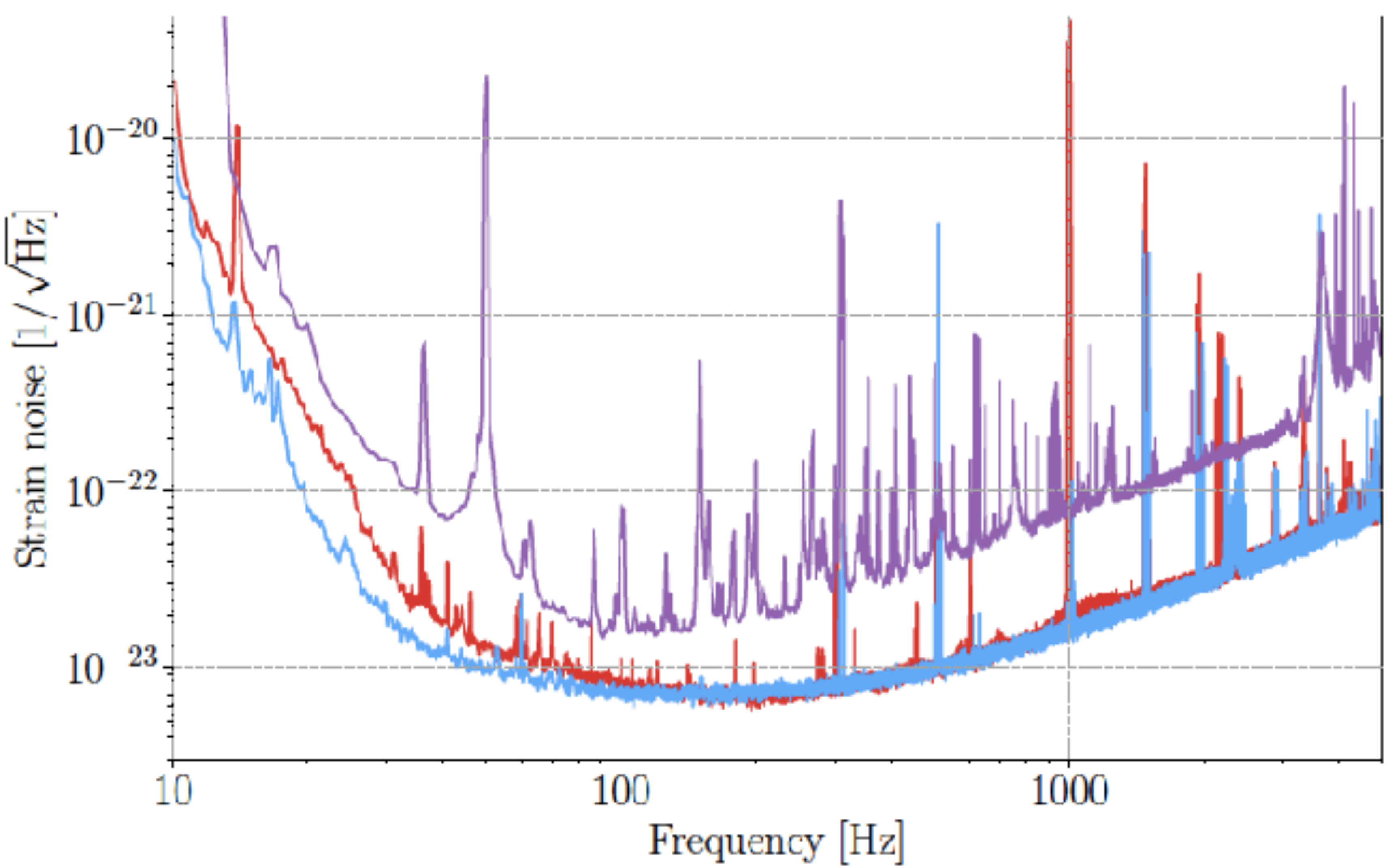
- LISA has been approved by ESA and is on the path to launch in 2032
  a new frequency range will be accessible, between Pulsar Timing Array and Earth-based interferometers, with great potential for cosmology

Advanced LIGO/Virgo interferometers

arm length L = 4 km

frequency range of detection: $10\,\mathrm{Hz} < f < 5\,\mathrm{kHz}$

- Black hole coalescing binaries of masses few to dozens solar masses
- Neutron Star and NS-BH binaries
- Stochastic GW background

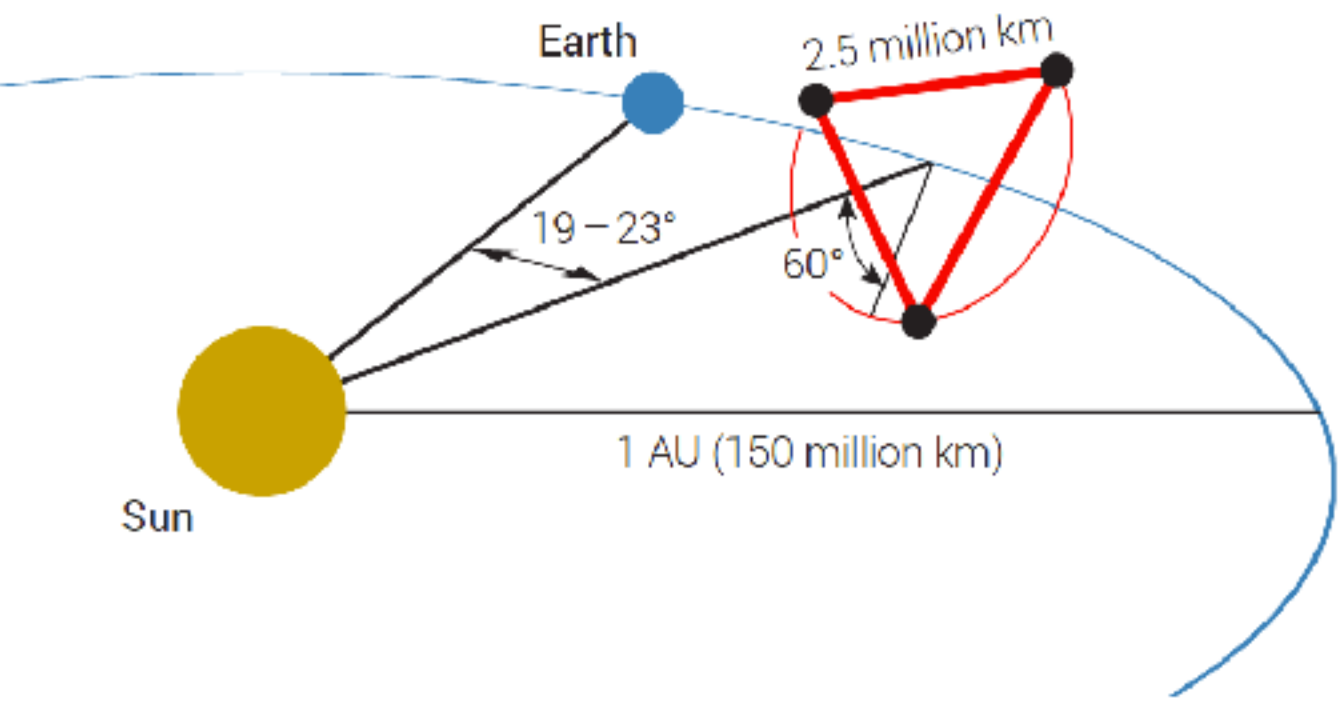


LIGO/Virgo arXiv:1811.12907

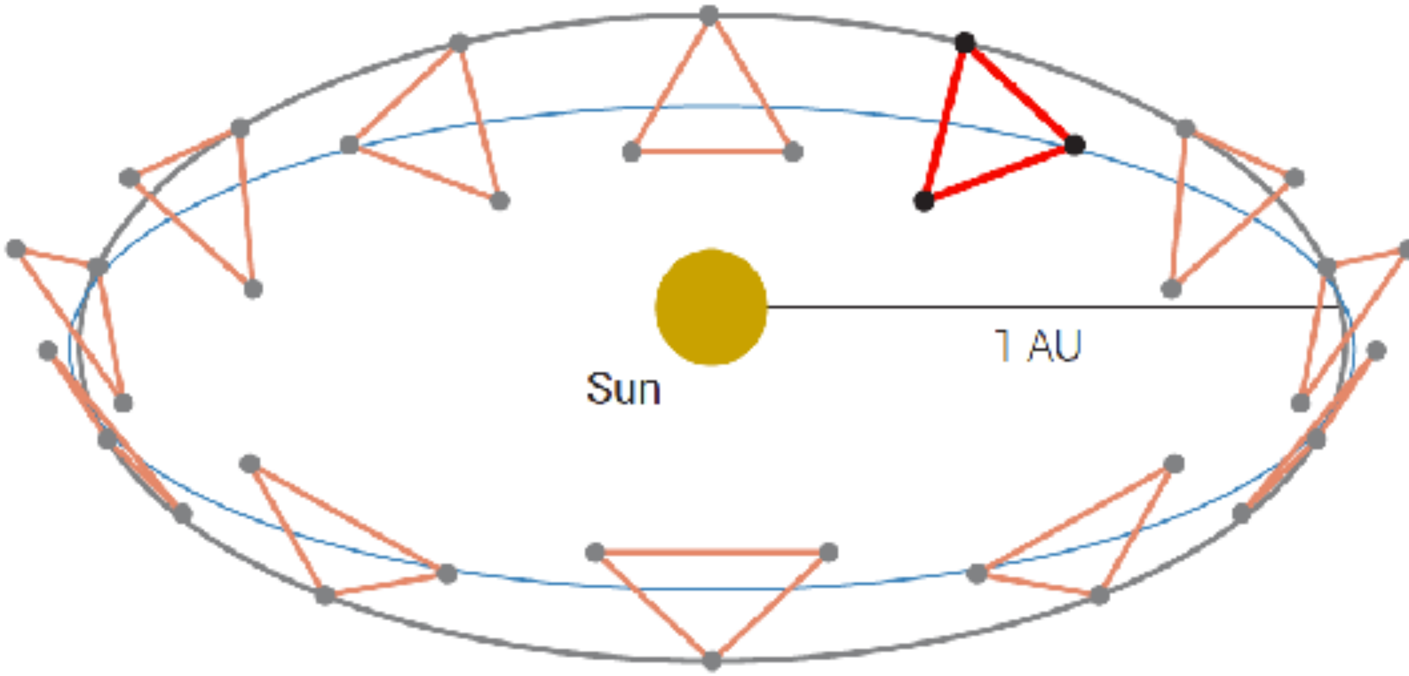
LISA: Laser Interferometer Space Antenna

- no seismic noise
- much longer arms than on Earth

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$



- Launch in ~2032
- two masses in free fall per spacecraft
- 2.5 million km arms
- picometer displacement of masses

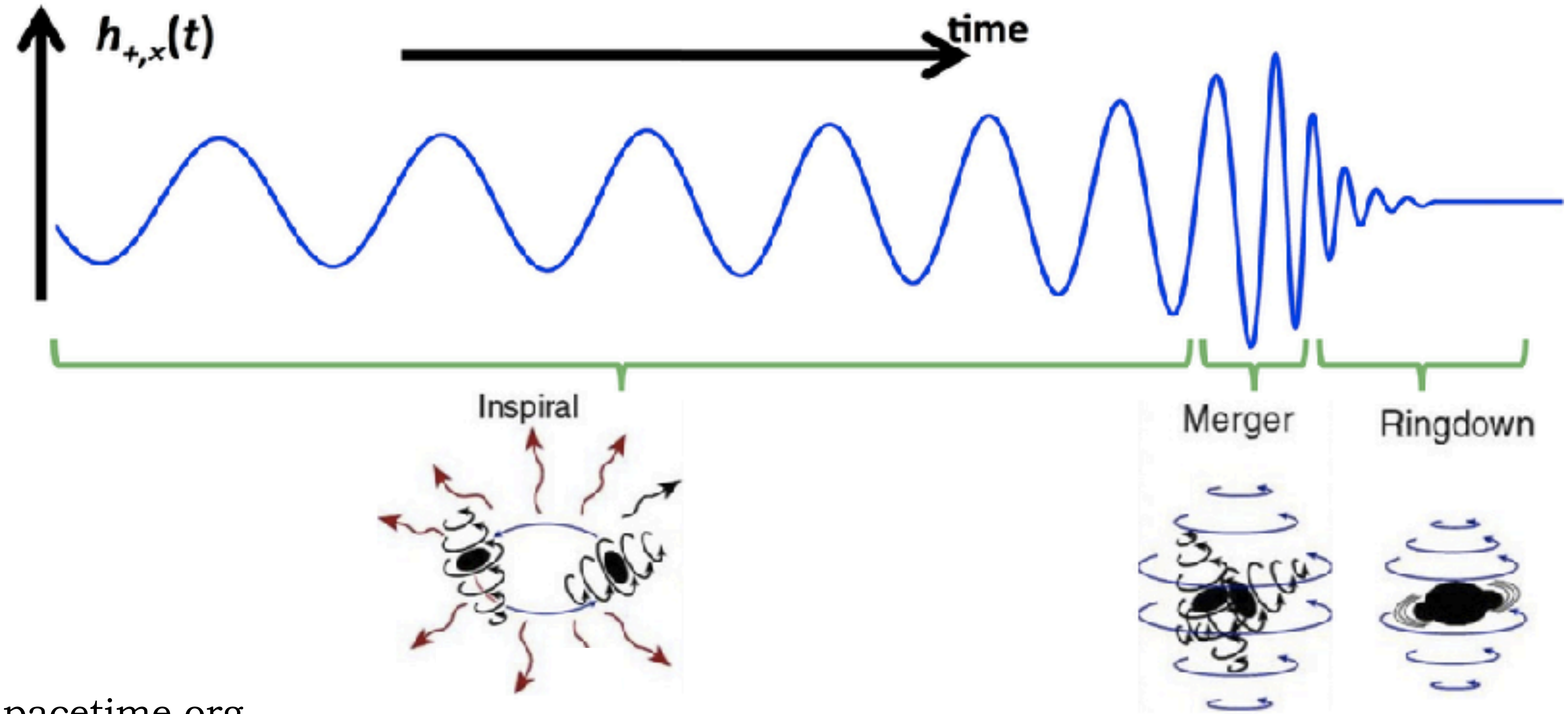


LISA collaboration arXiv:1702.00786

GW observables

1. The gravitational wave strain from the inspiral and merger of binaries of compact objects

$$h(t) \sim 2\,\frac{\Delta L}{L}$$



soundofspacetime.org

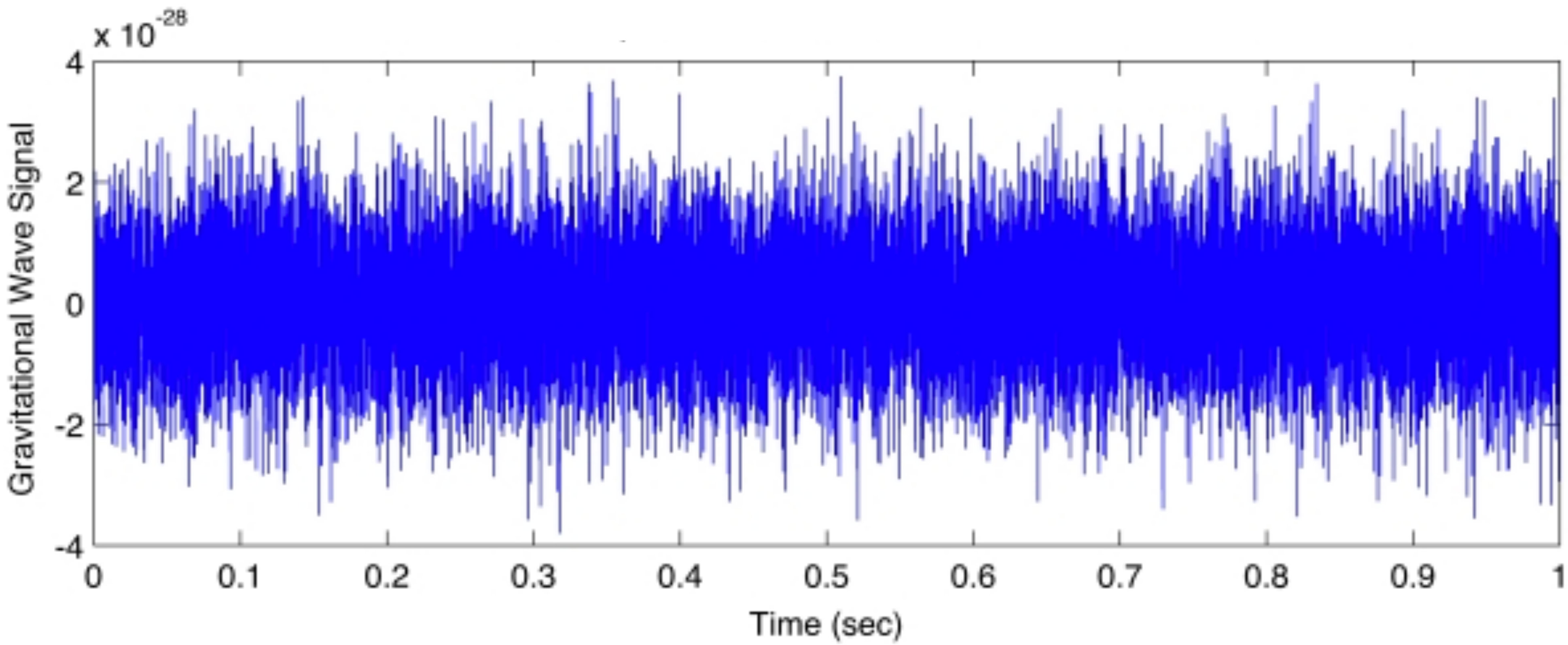
GW observables

2. the stochastic background of gravitational waves: the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the early universe with too small correlation scale with respect to the detector resolution

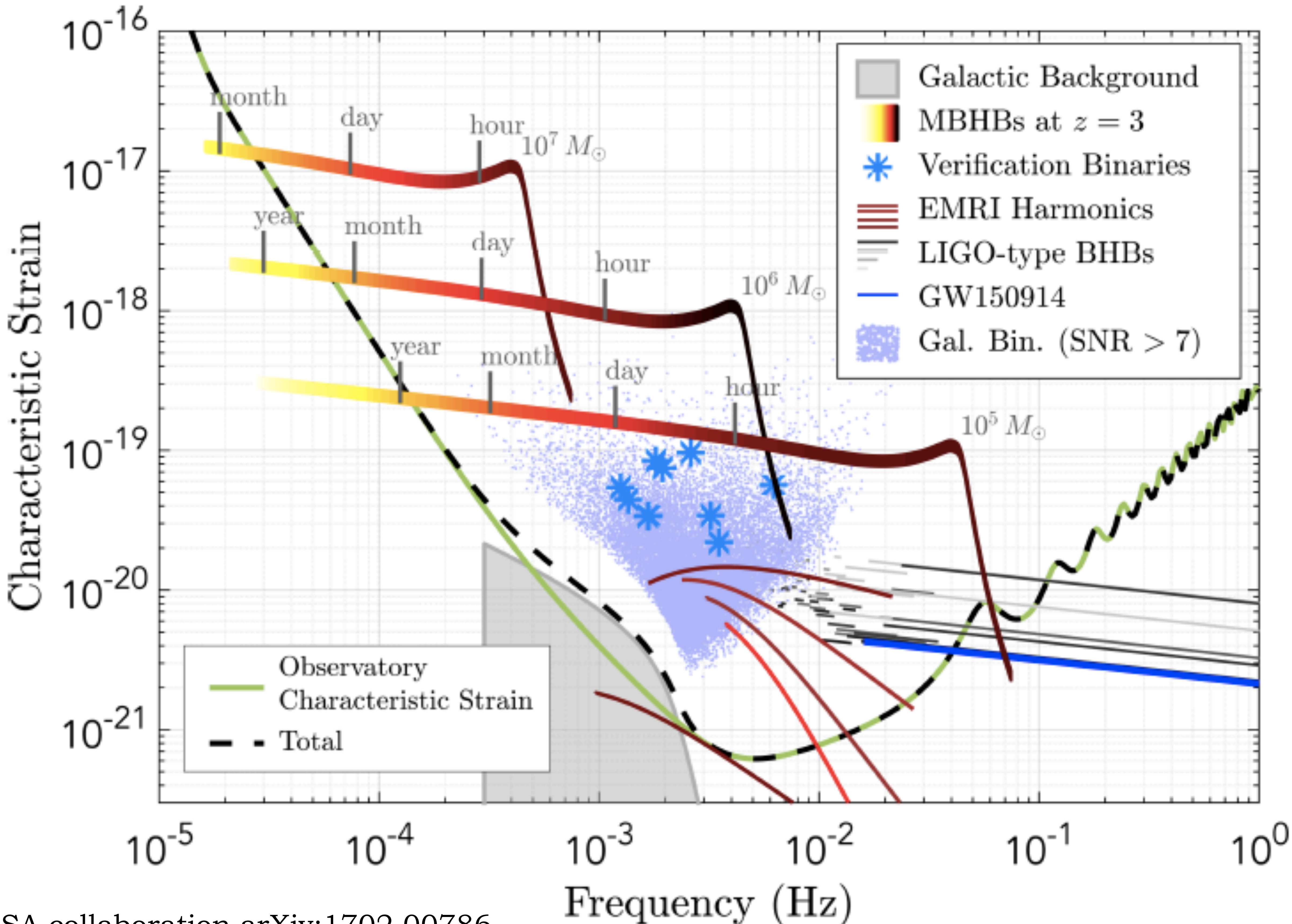
$$T^{00}_{\rm GW} \propto \frac{\langle \dot{h}_{ij}\dot{h}^{ij}\rangle}{G} \propto \int \frac{df}{f}\,\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f}$$

GW energy density power spectrum



LIGO website

Example: LISA sources



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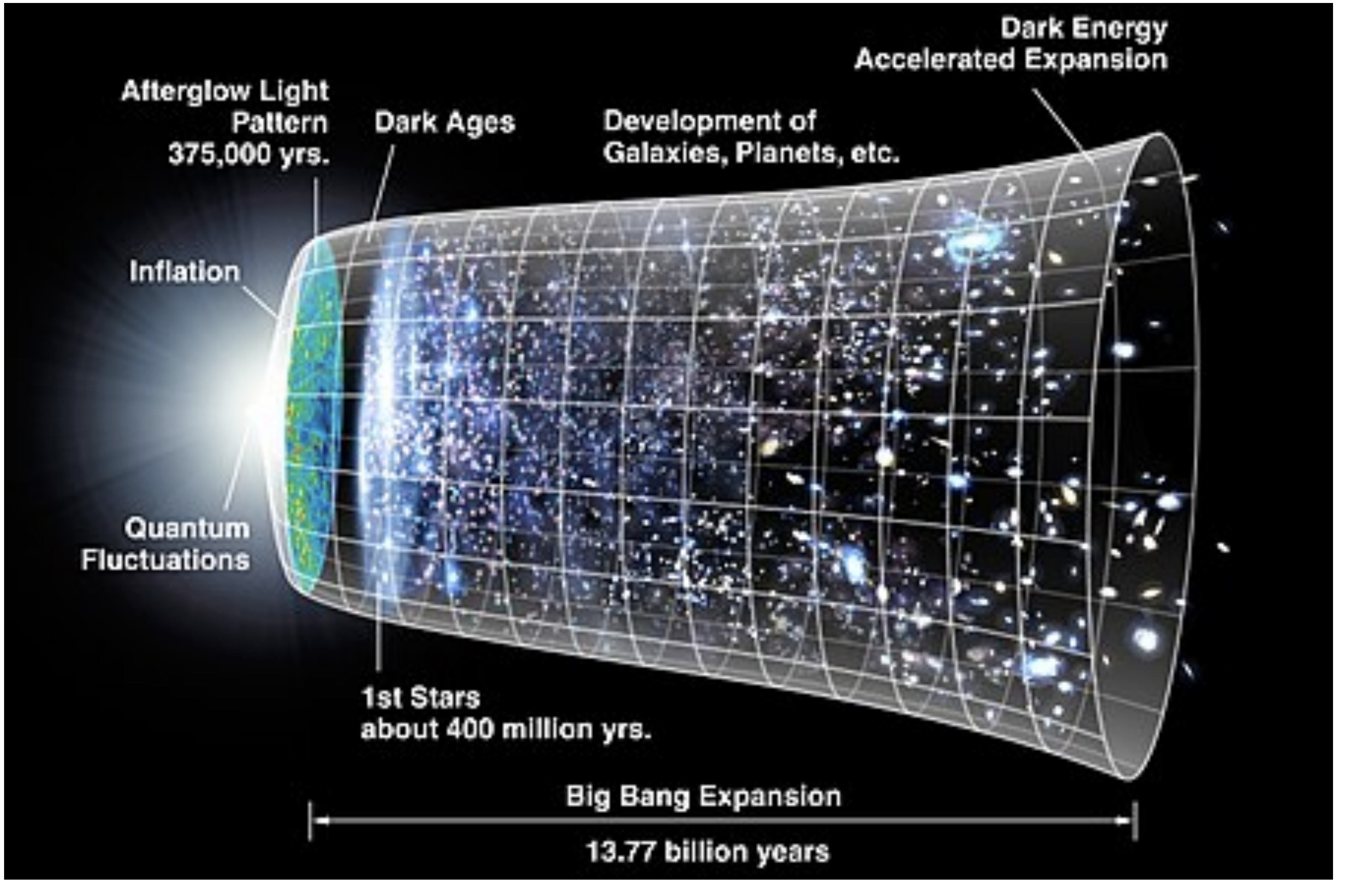
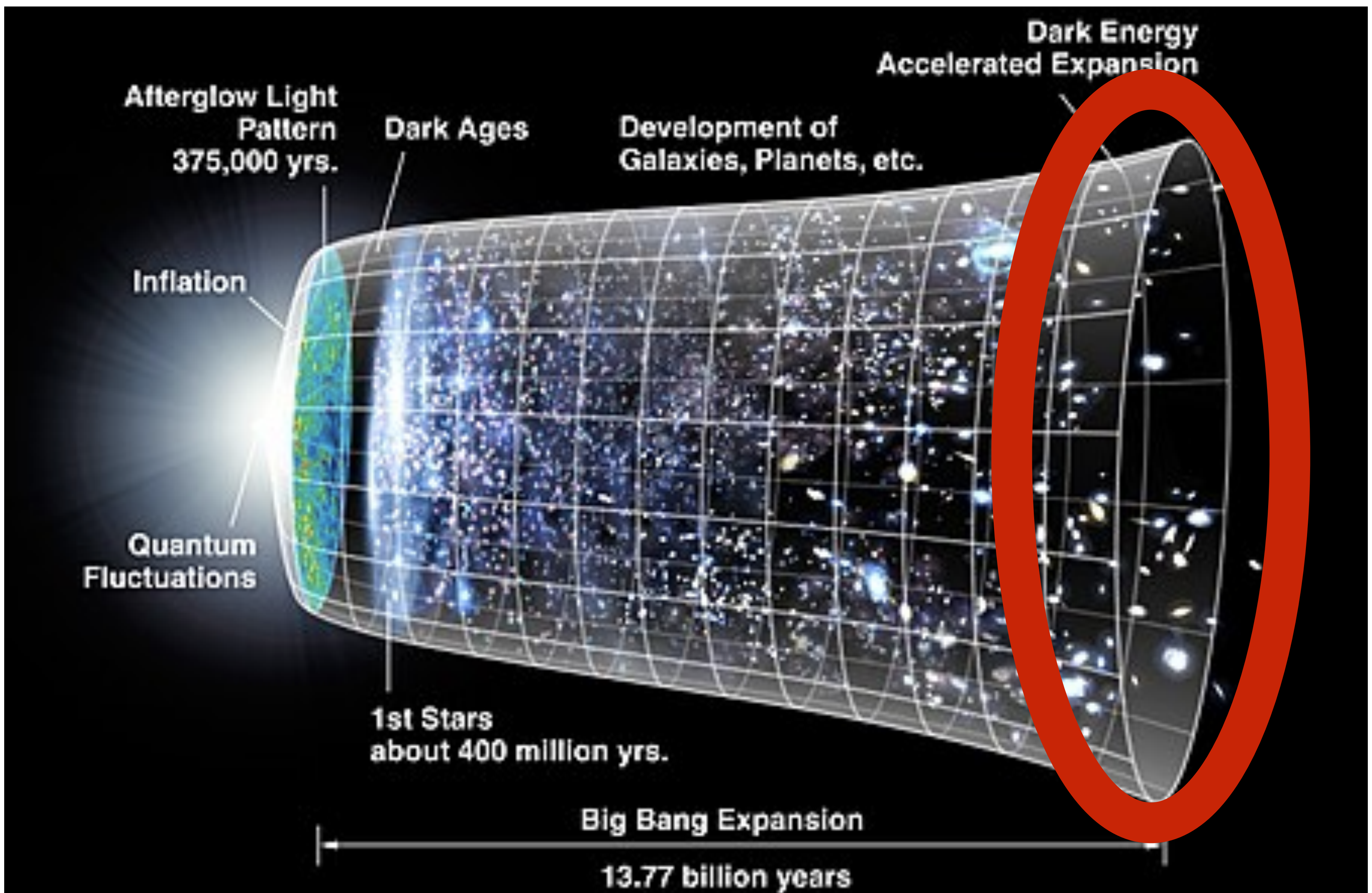
GW AND COSMOLOGY



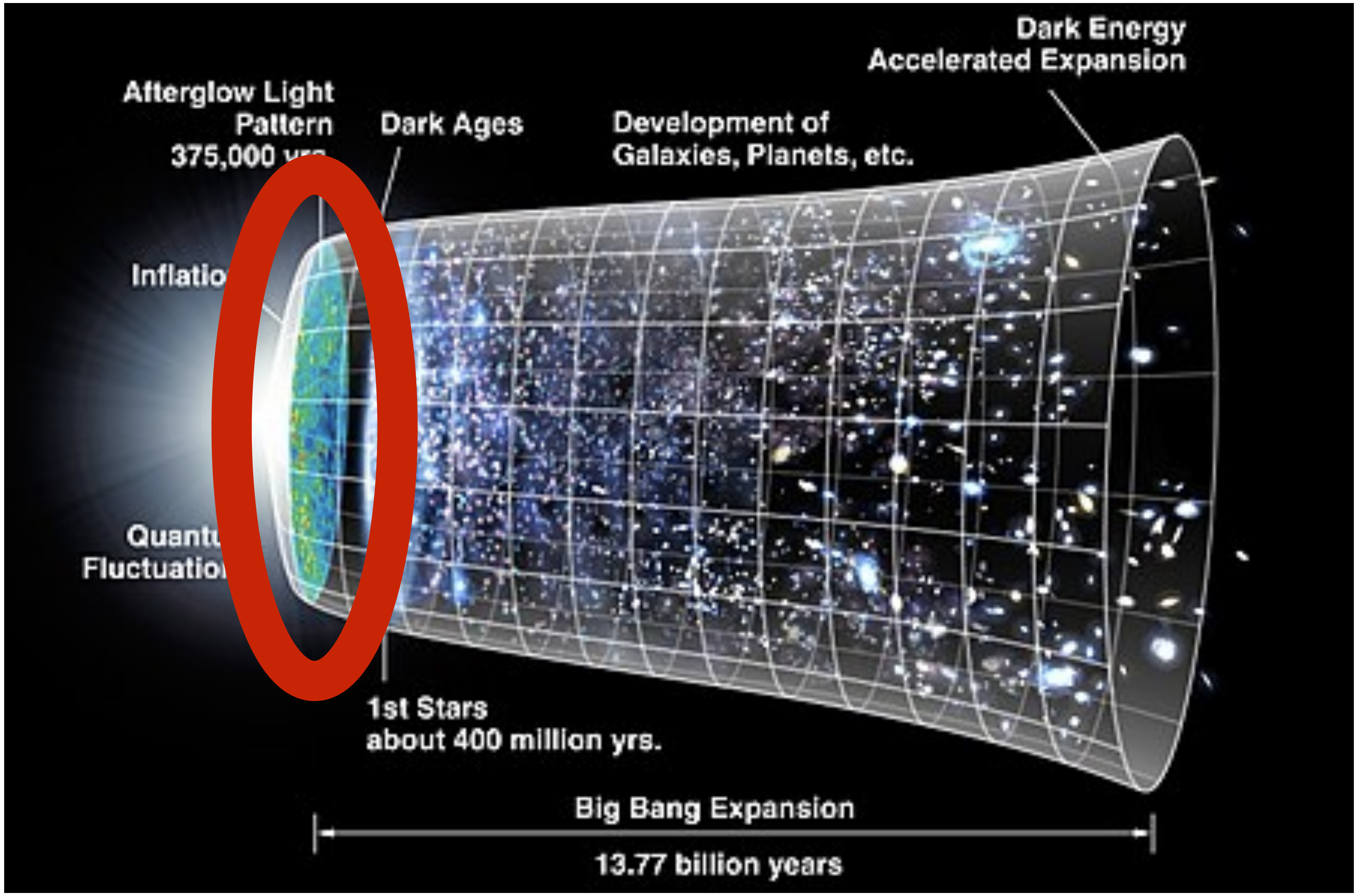
GW AND COSMOLOGY

use of GW emission from binaries to probe the background expansion of the universe: tests of acceleration

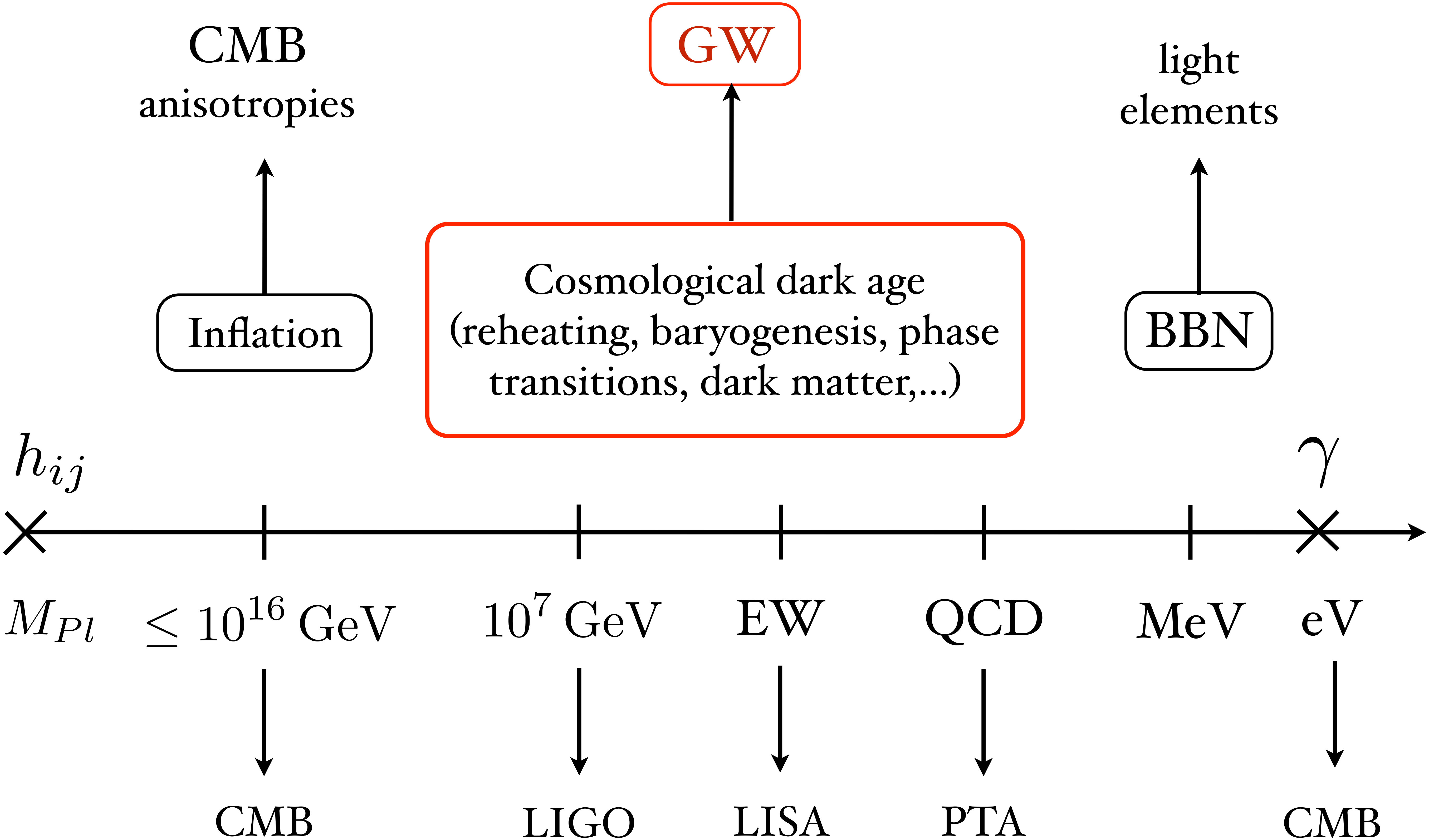


GW AND COSMOLOGY

the stochastic GW background from primordial sources:
test of early universe and high energy phenomena



GW from early universe sources



GW from early universe sources

- Since gravity is weak, GW propagate freely through the universe the GW signal from the early universe can be used as a probe of high energy physics

- The potential of GW to improve our knowledge of the universe is comparable to the one of the CMB at its dawn

- but do we expect primordial sources providing a GW signal high enough to be detectable?

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

$$|h_{ij}| \ll 1$$

$$h_i^i = \partial_j h_i^j = 0$$

superimposed on the homogeneous and isotropic background

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

WAVE EQUATION

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 0$$

source: amplification of vacuum fluctuations during inflation

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

WAVE EQUATION

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

source: Π_{ij}^{TT} tensor anisotropic stress

- fluid $\quad \Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$
- electromagnetic field $\quad \Pi_{ij} \sim (E^2 + B^2)\dfrac{\delta_{ij}}{3} - E_i E_j - B_i B_j$
- scalar field $\quad \Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$

GW sources in the early universe : inflation-related

- irreducible SGWB from inflation
    - also sourced by second order scalar perturbations
- beyond the irreducible SGWB from inflation
    - particle production during inflation (scalar, gauge fields… coupled to the inflaton)
    - spectator fields
    - breaking symmetries (space-dependent inflaton, massive graviton…)
    - modified gravity during inflation (massive GWs with $c \neq 1$)
    - primordial black holes
- alternatives to inflation
    - pre big-bang, cyclic/ekpirotic, string gas cosmology…
- preheating and non-perturbative phenomena
    - parametric amplification of bosons/fermions
    - symmetry breaking in hybrid inflation
    - decay of flat directions
    - oscillons

CC and Figueroa arXiv:1801.04268

GW sources in the early universe : phase transition-related

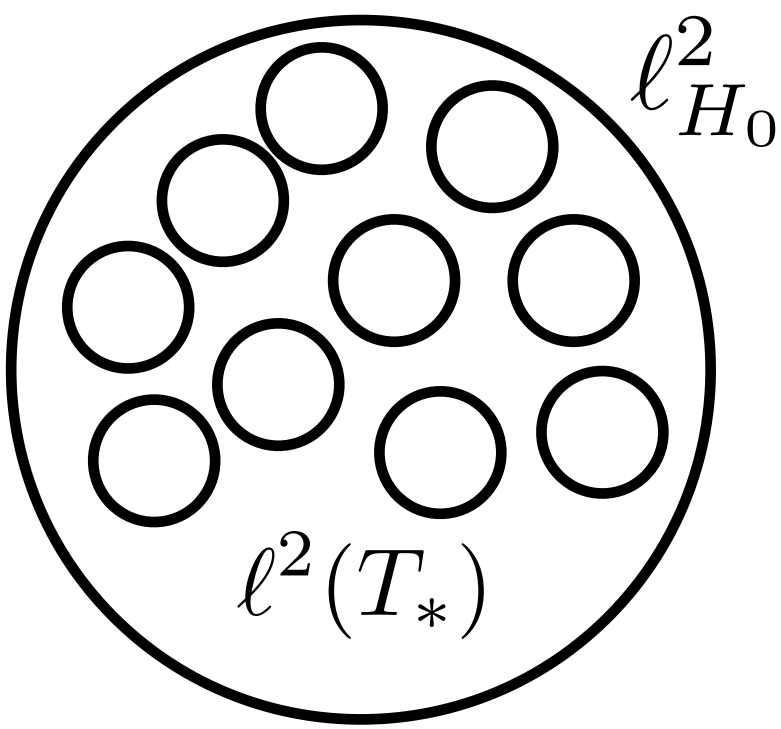
- first order phase transition
  - true vacuum bubble collision
  - sound waves
  - turbulence
- cosmic topological defects
  - irreducible SGWB from topological defect networks
  - decay of cosmic string loops

CC and Figueroa arXiv:1801.04268

Stochastic GW background

- sources from the early universe: stochastic background of GW statistically homogenous, isotropic, Gaussian and unpolarised
  - inflation: intrinsic, quantum fluctuations that become effectively classical (stochastic) due to the evolution
  - GW generated by anisotropic stresses at temperature T_* (or continuous sources): many independent horizon volumes visible today

causal source of GW cannot operate beyond the horizon (Hubble scale)



GW energy density power spectrum

$$\Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_c} = \frac{\langle \dot{h}_{ij}\dot{h}_{ij}\rangle}{32\pi G\,\rho_c} = \int \frac{{\rm d}f}{f}\frac{{\rm d}\Omega_{\rm GW}}{{\rm d}\ln f}$$

Characteristic frequency for *causal sources*

$$f_* = \frac{H(T_*)}{\epsilon_*}$$

parameter depending on the dynamics of the source

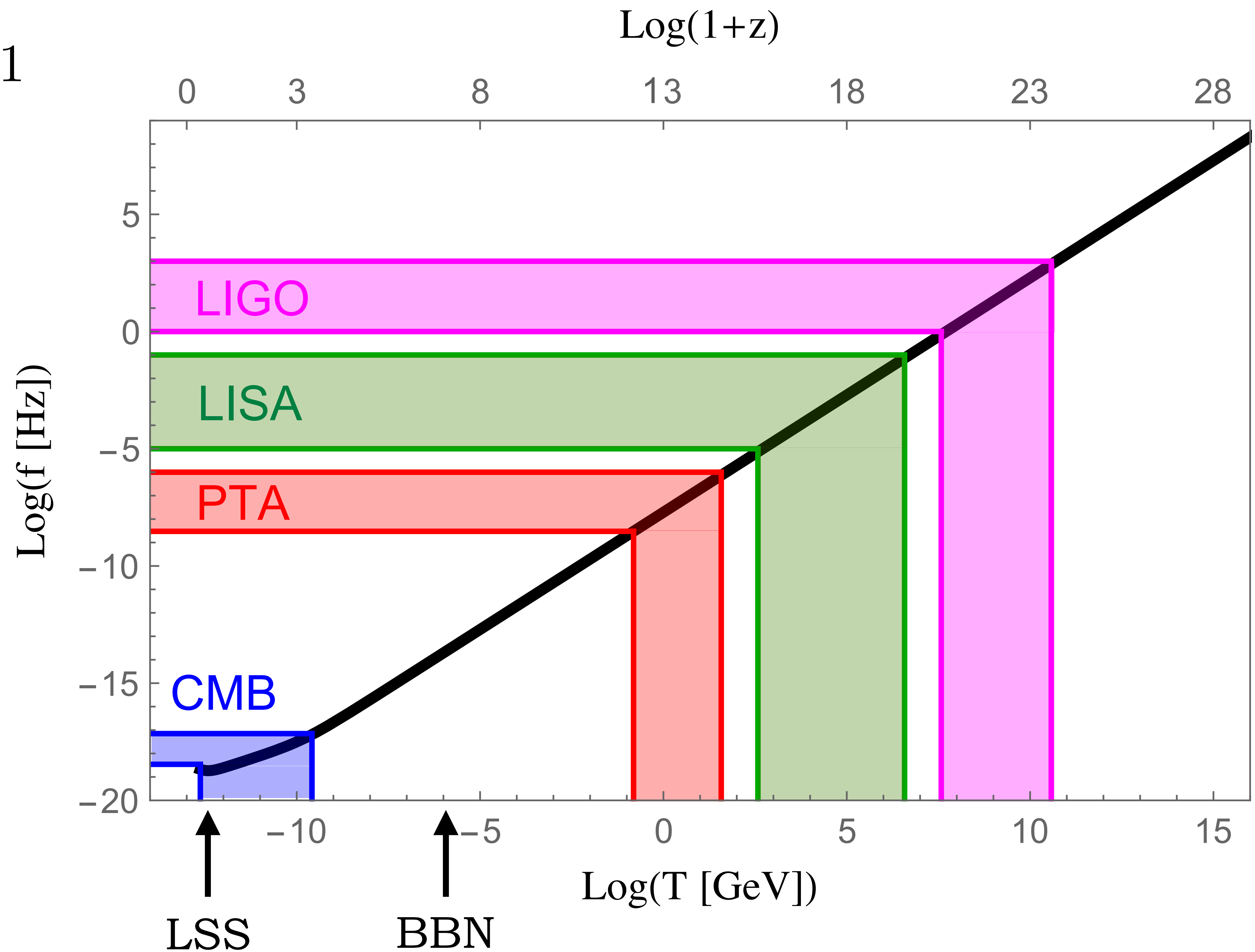
$$\epsilon_* = L_* H_*$$

characteristic scale of tensor stresses

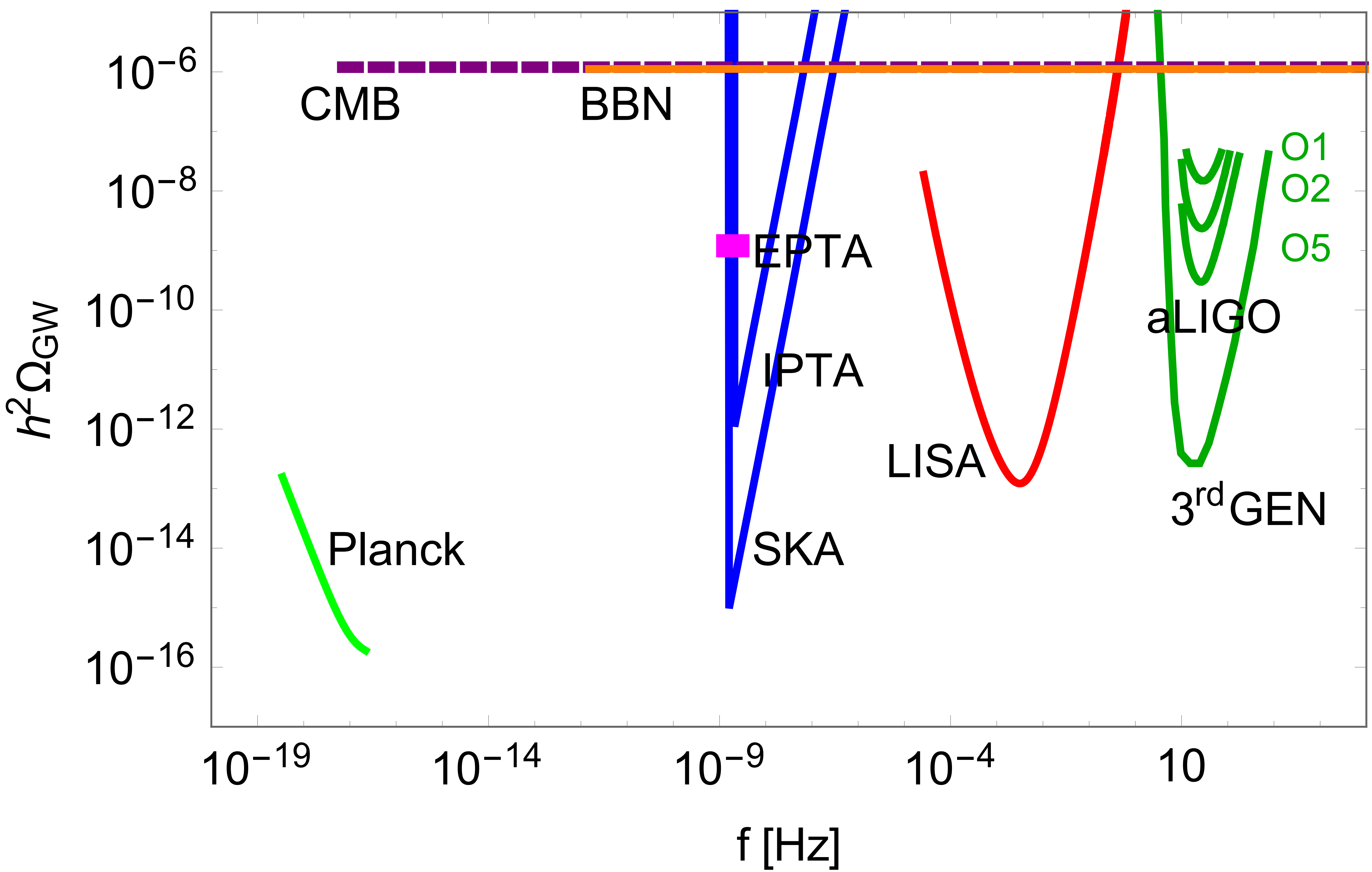
$$f_c = f_* \frac{a_*}{a_0} = \frac{2\cdot 10^{-5}}{\epsilon_*}\frac{T_*}{1\,{\rm TeV}}\,{\rm Hz}$$

Characteristic frequency for *causal sources*

$\epsilon_* = 1$



Bounds and detectors

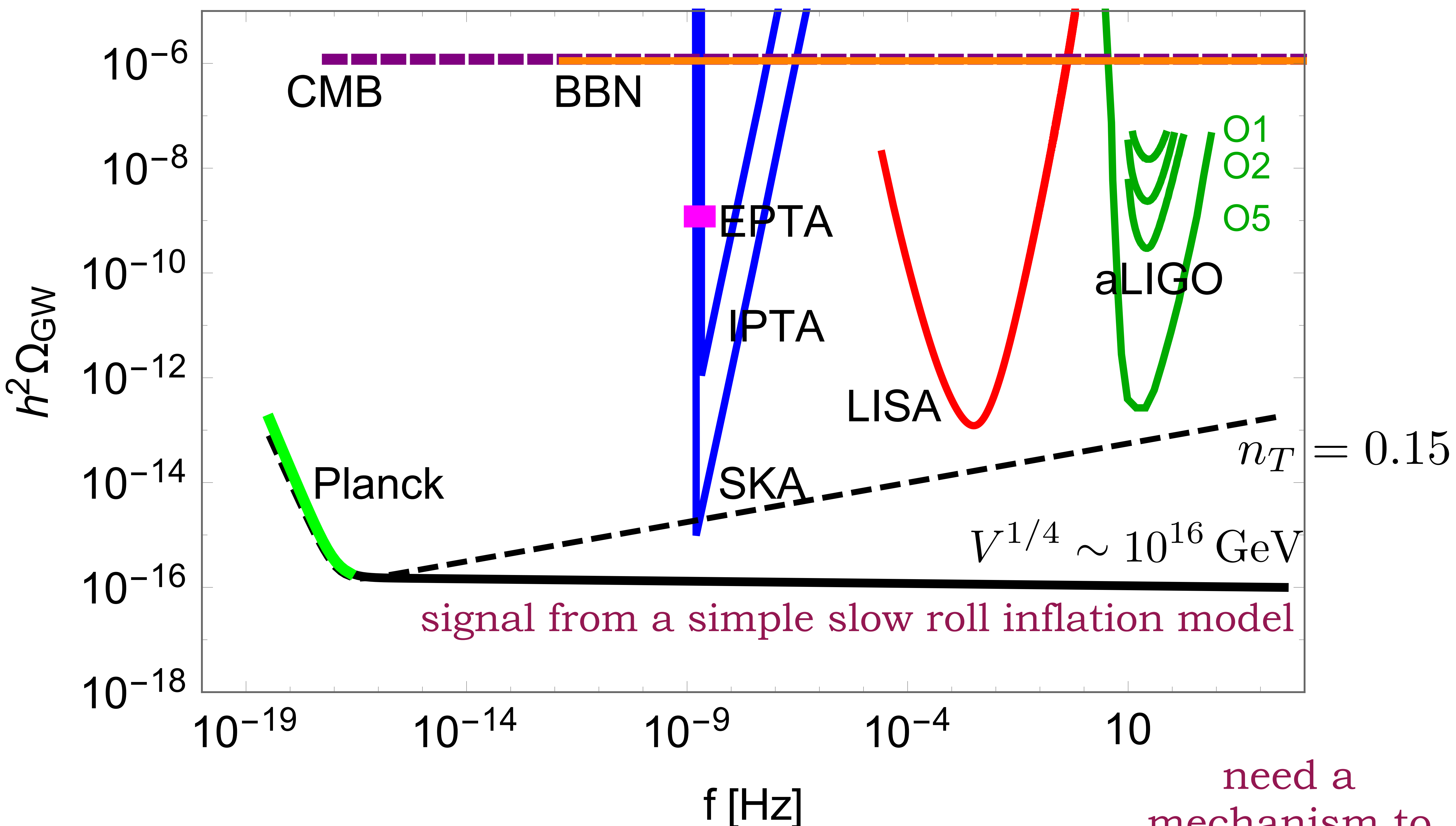


SGWB from slow roll inflation

$$\Omega_{\rm GW}(f) = \frac{3}{128}\,\Omega_{\rm rad}\, r\,\mathcal{P}^*_{\mathcal{R}}\left(\frac{f}{f_*}\right)^{n_T}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]$$

- tensor to scalar ratio $\quad r = \mathcal{P}_h/\mathcal{P}_{\mathcal{R}} \qquad r_* \leq 0.07$
- scalar amplitude at CMB pivot scale $\quad \mathcal{P}^*_{\mathcal{R}} \simeq 2\cdot 10^{-9} \qquad k_* = \frac{0.05}{\rm Mpc}$
- tensor spectrum $\quad \mathcal{P}_h = \frac{2}{\pi}\frac{H^2}{m^2_{Pl}}\left(\frac{k}{aH}\right)^{-2\epsilon} \qquad n_T \simeq -2\epsilon$
- transfer function from inflation to today

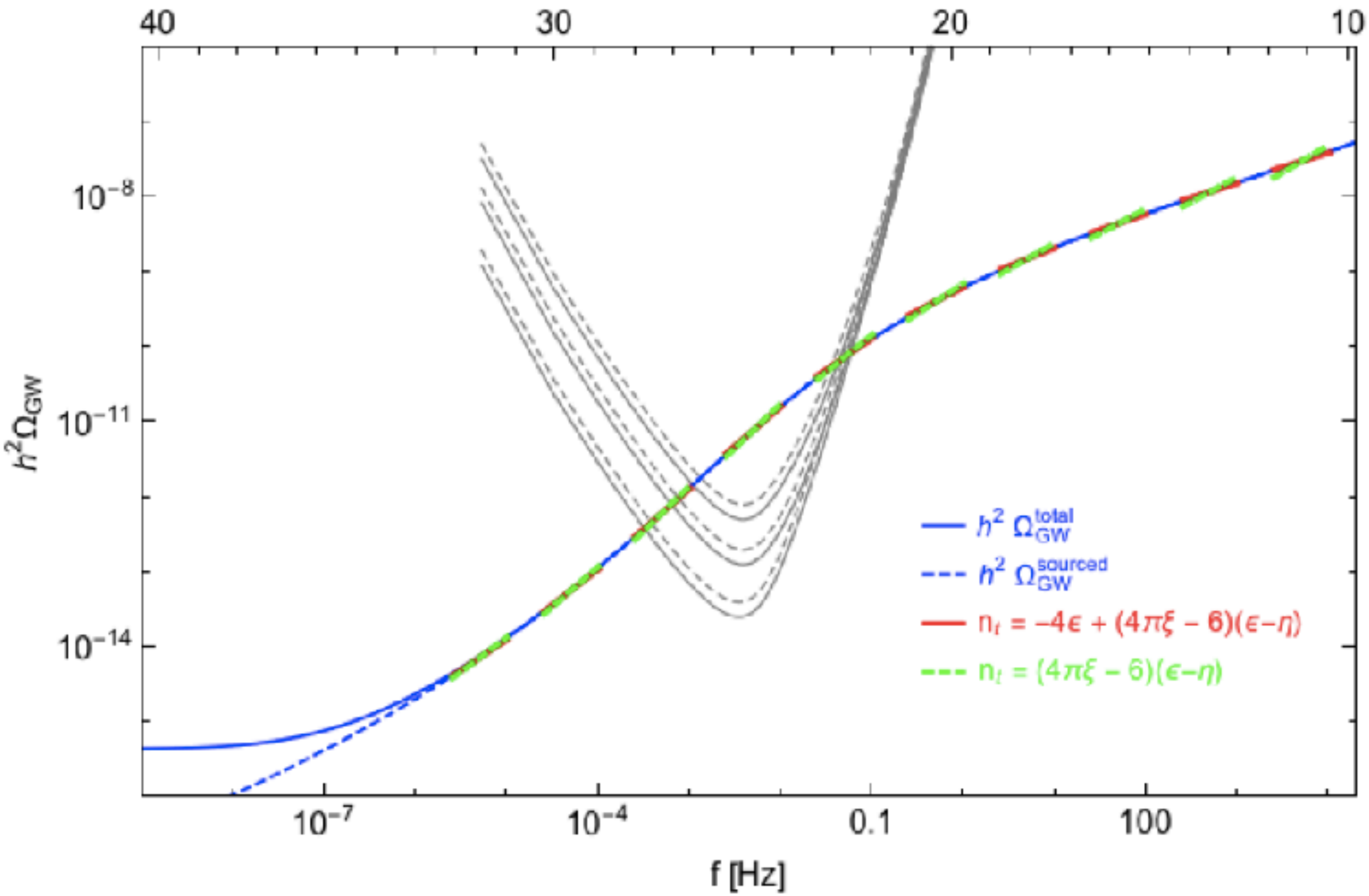
SGWB from slow roll inflation



need a mechanism to enhance it!

just one example: inflaton-gauge field coupling

$$\Delta\mathcal{L} = -\frac{1}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$\Lambda = \frac{M_{Pl}}{35}$$

quadratic inflaton potential

OTHER SIGNATURES:
non-gaussianity, chirality

N. Bartolo et al, arXiv:1610.06481
N. Bartolo et al, arXiv:1806.02819

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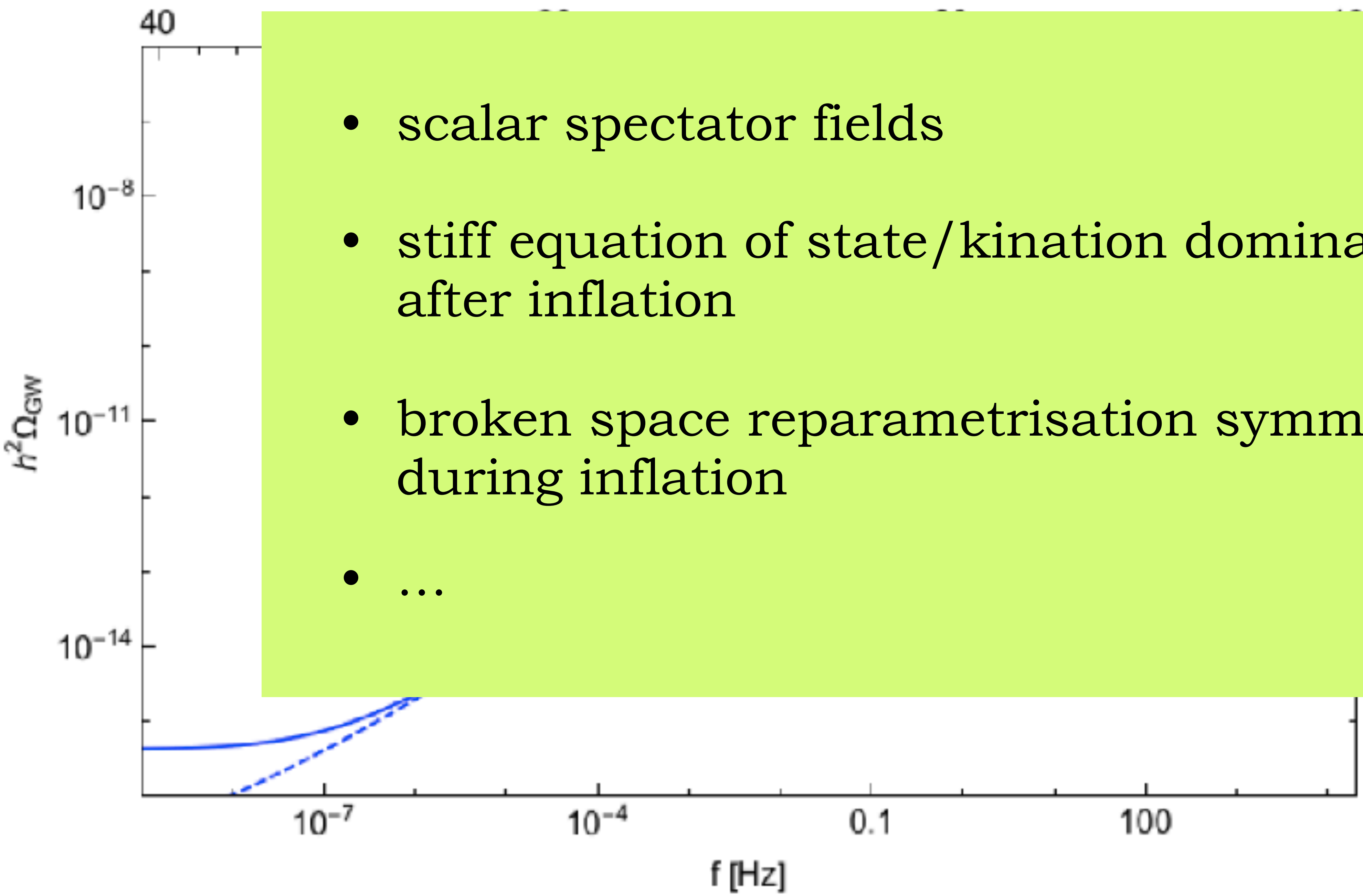
$$\Delta\mathcal{L} = -\frac{1}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



- scalar spectator fields
- stiff equation of state/kination domination after inflation
- broken space reparametrisation symmetry during inflation
- ...

$$\Lambda = \frac{M_{Pl}}{35}$$

quadratic inflaton potential

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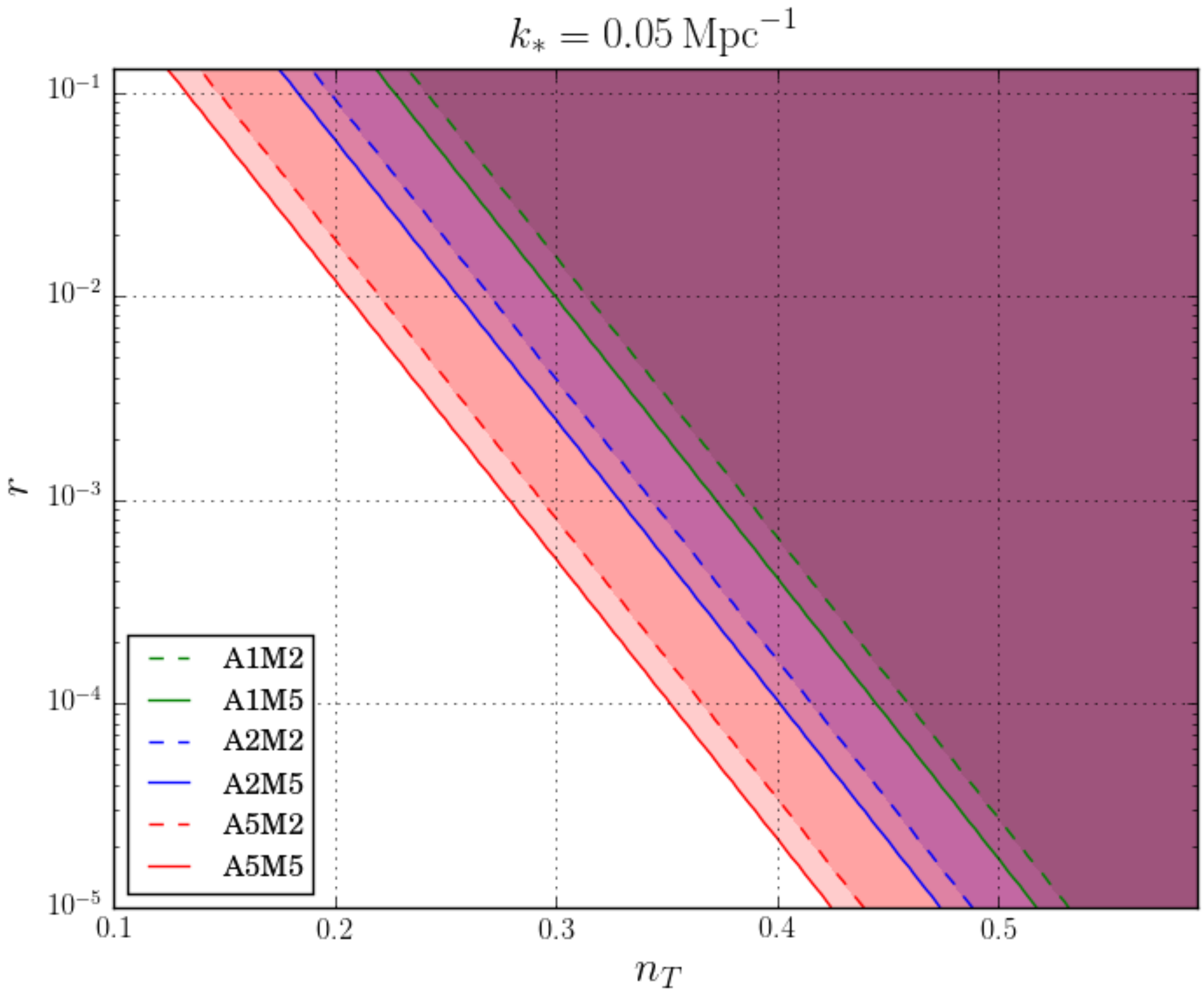
general constraints on (r,n_T) from LISA

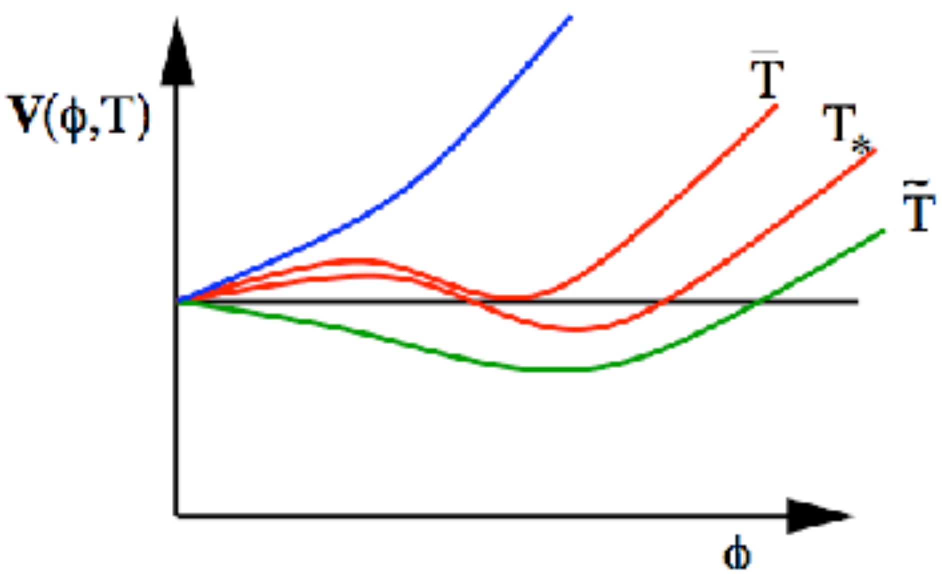


N. Bartolo et al, arXiv:1610.06481

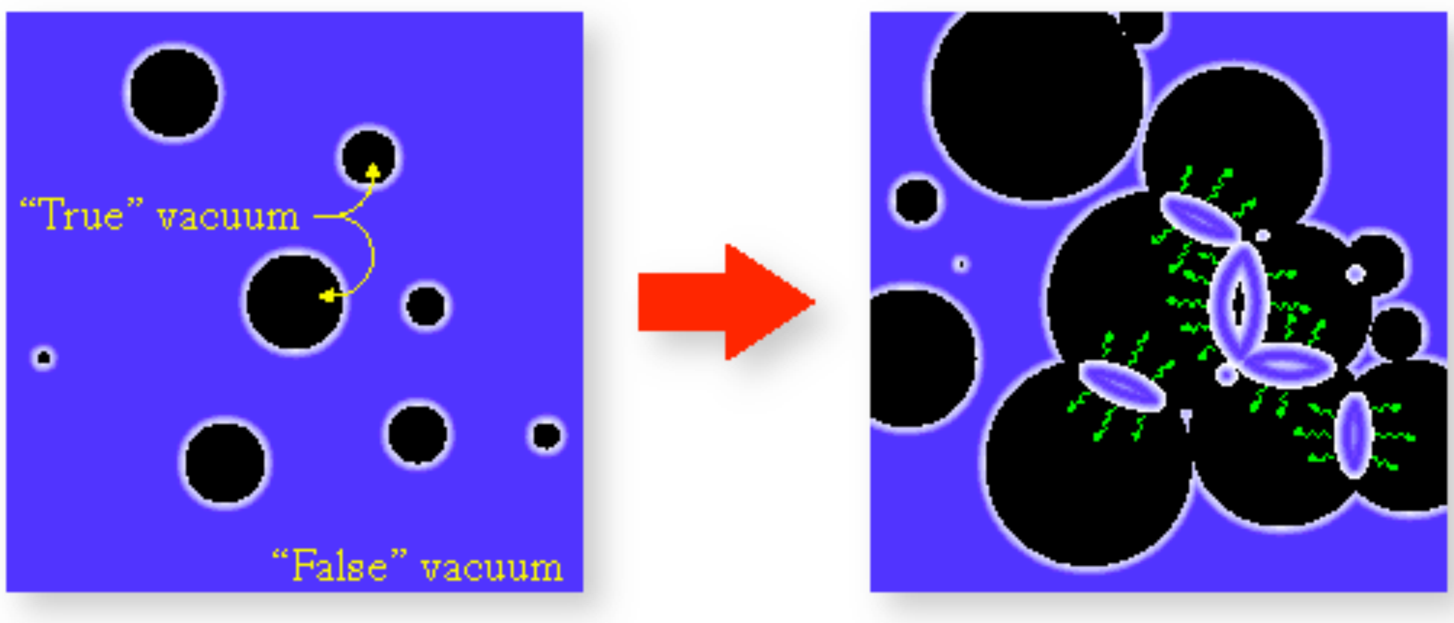
SGWB from first order phase transitions

in the course of its adiabatic expansion, the universe
might have undergone several PTs, maybe of first order

potential barrier separates true and false vacua



quantum tunneling across the barrier : nucleation of bubbles of true vacuum



- QCD and EWPT (beyond the standard paradigm)
- higher temperature PTs (extra dimensions, dark matter models…)

SGWB from first order phase transitions

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

- collisions of bubble walls $\quad \Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$

- sound waves and turbulence in the fluid $\quad \Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$

- primordial magnetic fields (MHD turbulence)

$$\Pi_{ij} \sim (E^2 + B^2)\frac{\delta_{ij}}{3} - E_i E_j - B_i B_j$$

SGWB from first order phase transitions

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

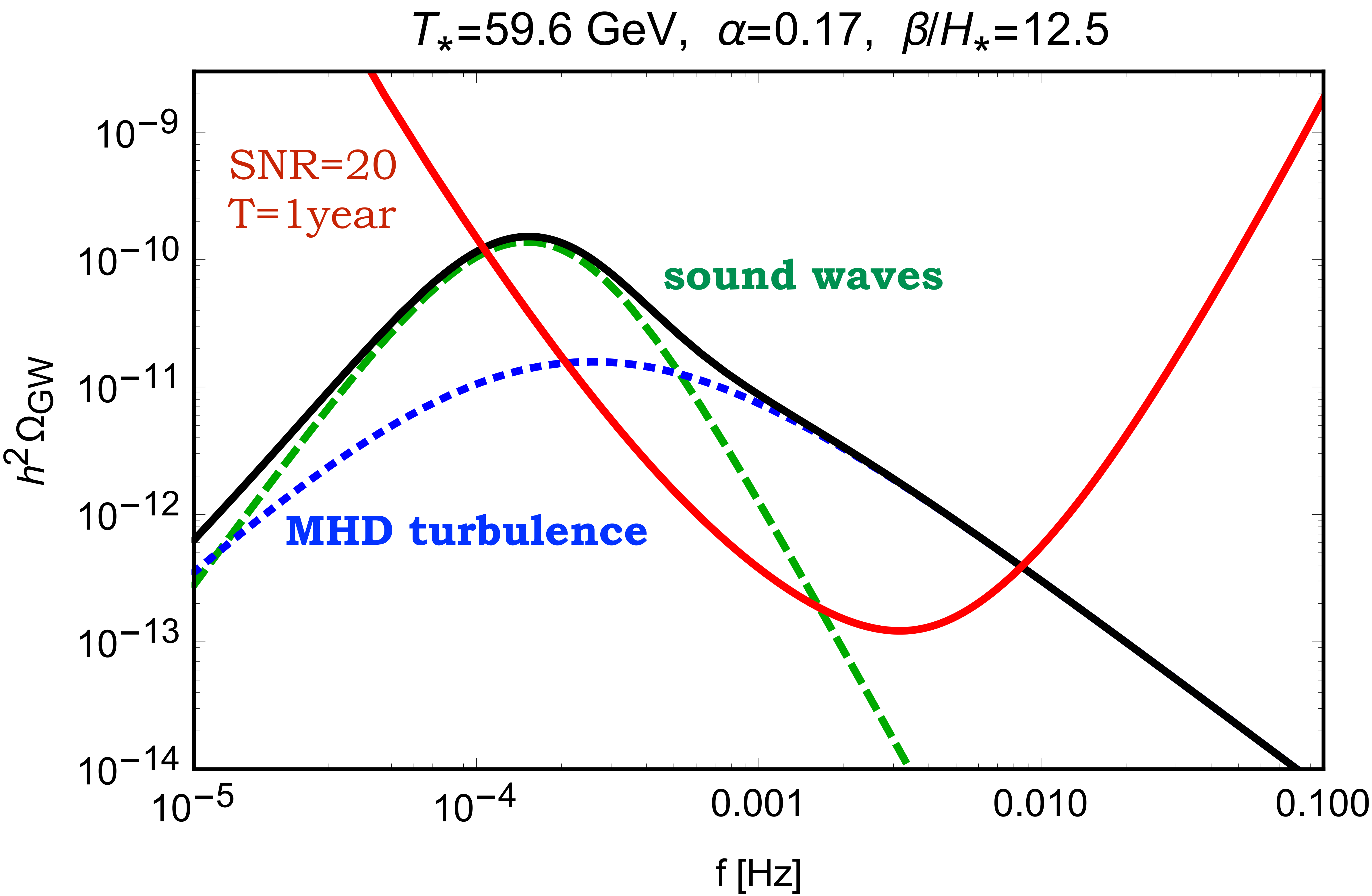
- LISA (mHz) is sensitive to energy scales around the TeV scale, so it can can probe the EWPT in BSM models and more exotic PTs beyond the EWPT

connections with baryon asymmetry, dark matter : LISA as a probe of BSM physics, complementary to colliders

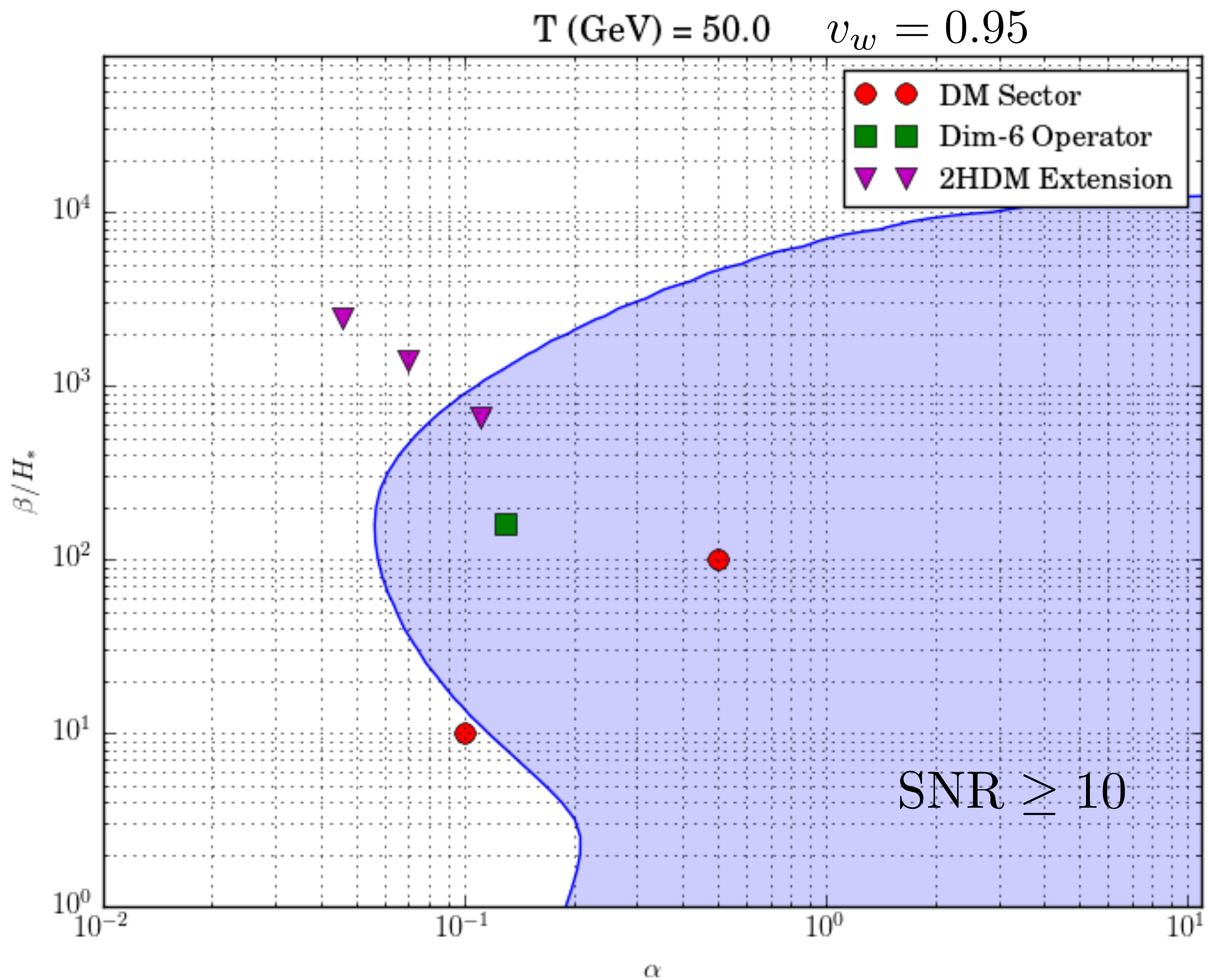
- Pulsar Timing Array (nanoHertz) can probe the QCDPT scale at 100 MeV

- Earth-based detectors (100 Hz) can probe more exotic PTs possibly occurring around 10^5 GeV

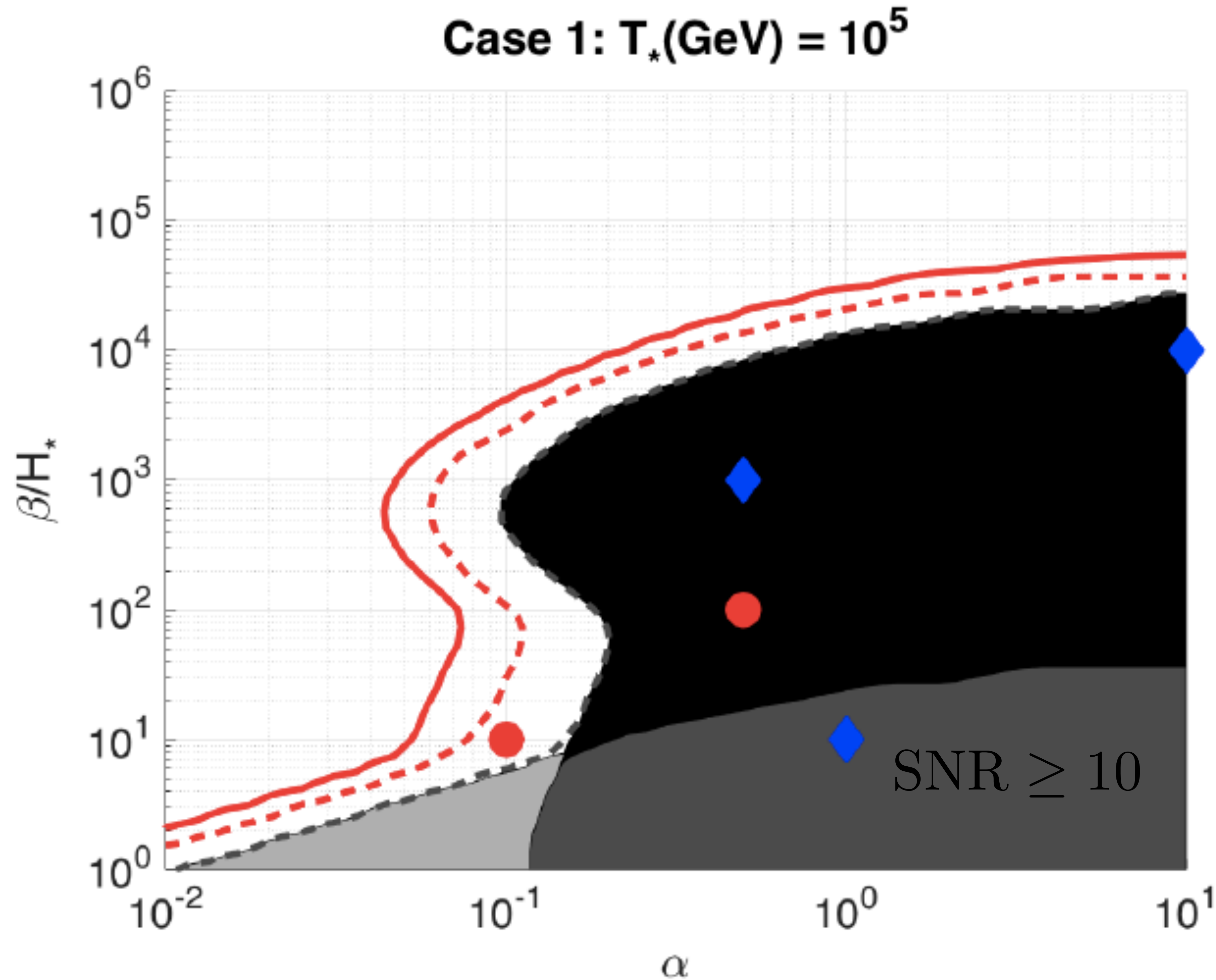
Example of signal from FO EWPT in LISA



Example of detection prospects for LISA: EWPT and beyond



Example of detection prospects for 3rd generation Earth-based interferometers: more exotic PT



GW background from cosmic strings

- depending on their nature, can radiate GW : predictions on the signal are possible only within given models

- constraints on their energy scale $\eta \sim M_{\rm Pl}\sqrt{G\mu}$ through $G\mu$

- global strings : lower bound on GW emission (constraints from GW not competitive with, e.g. CMB)

- Nambu Goto local strings: loop size and loop distribution?

future GW (LISA): $G\mu < \mathcal{O}(10^{-17})$

future CMB B-modes

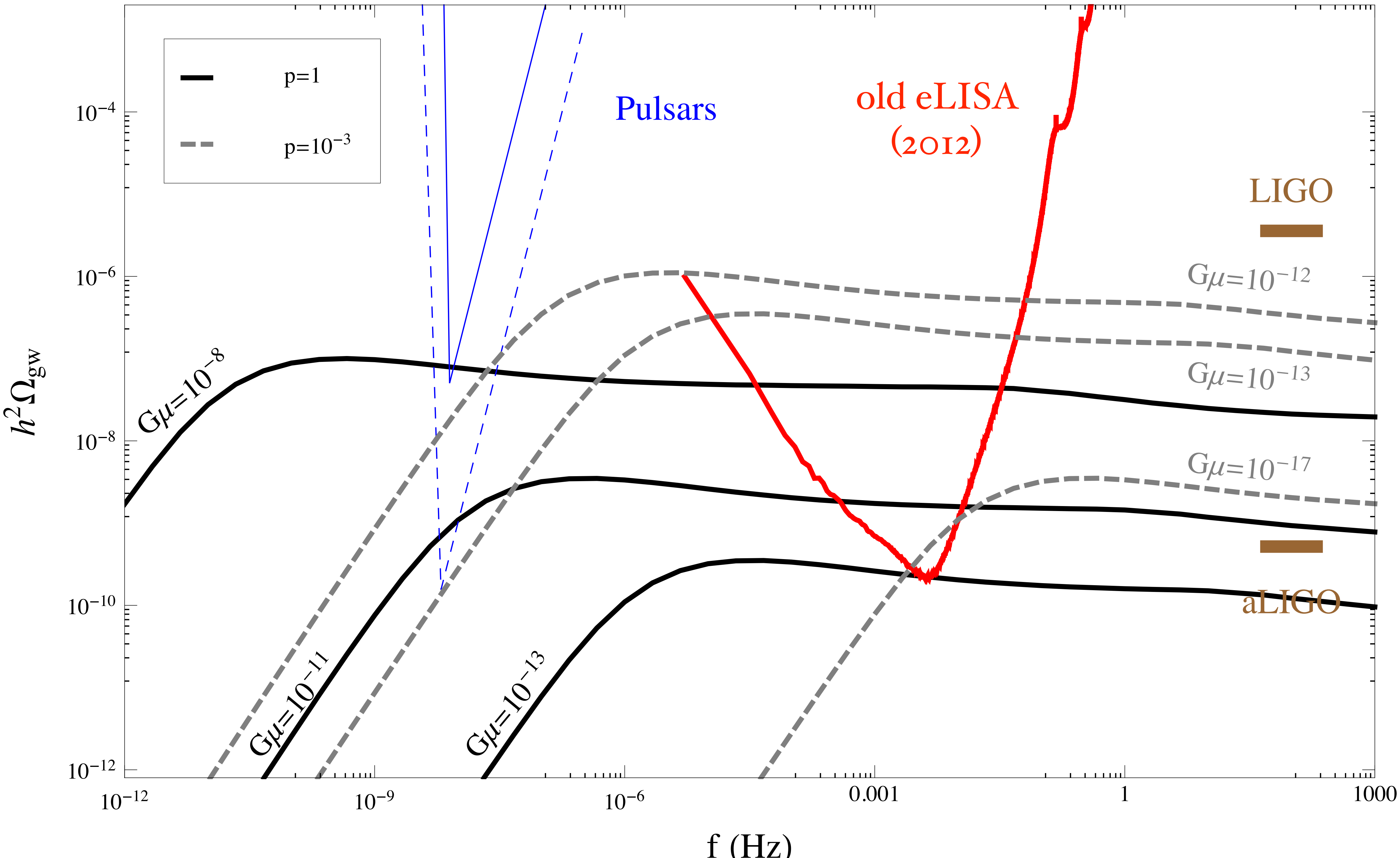
$G\mu < 10^{-9}$

Future SKA

$G\mu < 10^{-13}$

Nambu-Goto strings, large loops

spectral shape extended in frequency because of continuous production



Binetruy et al 2012

Conclusions

LIGO/Virgo detections have opened the era of GW astronomy and cosmology (measurement of H_0, tests of $GR_{...}$)

LISA is on the path to launch in 2034 and it has the potential to probe the early universe and late-time cosmology

there can be a cosmic relic SGWB which, if detected, will bring information on the very early universe and high energy physics (complementary to particle colliders)

LISA can test non-standard inflationary models, the EW symmetry breaking and beyond, cosmic strings…